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Spin-Isospin Excitations in Nuclei via (^{3}He,t) Reactions at 450 MeV

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Spin-isospin excitations in nuclei have been studied by means of the (^{3}He,t) reactions at 450 MeV The Gamow-Teller (GT) resonances are found to be strongly excited A fine structure of the giant Gamow Teller resonances in medium-heavy nuclei is observed with an energy resolution of 130 keV The volume integrals of the effective interactions $J_{\sigma\tau}$ and J_τ have been determined experimentally The importance of high resolution observation of the (^{3}He t) reactions at intermediate energies, both, to study the double β decay processes and to measure the detection sensitivities for solar neutrino experiments is discussed

1. INTRODUCTION

Over the last fifteen years, collective spin-isospin excitations in nuclei have been extensively studied by (p n) reactions at intermediate energies since the discovery of the Gamow-Teller (GT) resonances in the late 70's [1–3] The GT resonances were theoretically predicted thirty years ago to explain the retardation of Gamow-Teller β-decays compared to single-particle estimates [4, 5] The spin-flip ΔL=1 resonances were, subsequently, predicted to explain the retardation of first-forbidden β-decay [6]

The spin-isospin excitations in nuclei have been one of the interesting subjects of experimental and theoretical investigations for a long time The missing strength of the Gamow-Teller excitations is still an unresolved problem, the solution of which may

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require detailed information on nuclear short range correlations as well as on excitations of the nucleon itself On the other hand, the detailed information on the nuclear response functions for the operators $\sigma\tau$ and $\sigma\tau r Y_1$ is very useful for the application of nuclear physics to other fields The Gamow-Teller and first-forbidden transition matrix elements for specific nuclei are crucial input for various fundamental studies such as the detection efficiency for solar neutrinos [7], which is at present one of the most important subjects in astrophysics as well as in particle physics, which is related to the problem of neutrino oscillations The study of the spin-isospin responses of nuclei including the Gamow-Teller resonances is also important to check the validity of theories for the double β processes, which is related to the presence of massive electron neutrino or the Majorana type neutrino At present, these studies require the deep understanding of the microscopic structures of the spin-isospin excitations in nuclei, for which high resolution measurements at intermediate energies are essential

The Gamow-Teller resonances have been studied by various charge-exchange reactions such as (^{3}He t) and (^{6}Li, ^{6}He) which take advantage of high resolution and high detection efficiency In particular the (^{3}He,t) reaction has been used to observe the GT strengths at various bombarding energies E$\leq$100 MeV/u [8–14] It is now clear that the extraction of GT strengths from the (^{3}He,t) cross sections at low-bombarding energies is more difficult than for the (p n) reactions at E$\geq$100 MeV due to the dominance of the two-step reaction mechanisms and of non-central interactions like tensor forces

However, the (^{3}He t) reaction becomes a very suitable alternative to investigate the spin-isospin excitations when the bombarding energies exceed 100 MeV/u This has been experimentally demonstrated by the (^{3}He t) work at Saclay [15], and more recently at RCNP [16] In particular, successful operation of the new high resolution spectrometer, Grand Raiden [18] at RCNP enables the advantageous application of high-resolution spectroscopic studies to further the understanding of spin-isospin modes of excitation in nuclei New attempts of studying the spin-isospin excitations by the (^{3}He t) reaction are now in progress by taking advantage of selective excitations of the Gamow-Teller resonance at zero degree and at the high bombarding energy E=450 MeV with high resolution

2. Experiment

The present experiment was carried out at the Ring Cyclotron facility of the Research Center for Nuclear Physics with a 450 MeV ^{3}He beam, and with a new spectrometer Grand Raiden [18] The 450 MeV $^3He^{2+}$ beam was dispersively transported from the cyclotron to the scattering chamber without any energy-defining slits in order to reduce the beam halo The dispersion matching technique was applied to obtain high-resolution (^{3}He t) spectra at 0° The targets used were metallic foils with the thicknesses of 4~7 mg/cm^2 The vertical and horizontal defining angles were respectively, set at $\pm$20 mr

The $^3He^{2+}$ beam passing through the target entered the spectrometer, and was stopped in a special Faraday cup prepared at an inside wall of the vacuum chamber of the first dipole (D1) magnet The outgoing tritons were momentum analyzed with the spectrometer and detected by the focal-plane counter system, which consisted of two 2-dimensional position-sensitive multi-wire drift chambers (MWDC) and two ΔE-scintillation counters for particle identification The best resolution of about 130 keV was achieved In addition to triton peaks due to the (^{3}He,t) reaction, a strong peak due to $^{3}He^{+}$ events was observed at the high-momentum side of the focal plane The $^{3}He^{+}$ particles were measured simultaneously with the tritons and were used to calibrate both the energy and the scattering angles of the detected tritons The horizontal and vertical scattering angles at the target could be determined by ray-tracing techniques using information on the incidence angle of tritons at the focal plane The obtained data at 0° with the solid angle of 1 6 msr were further divided into data with individual narrow cones at small scattering angles in order to estimate the angular distributions at very forward angles

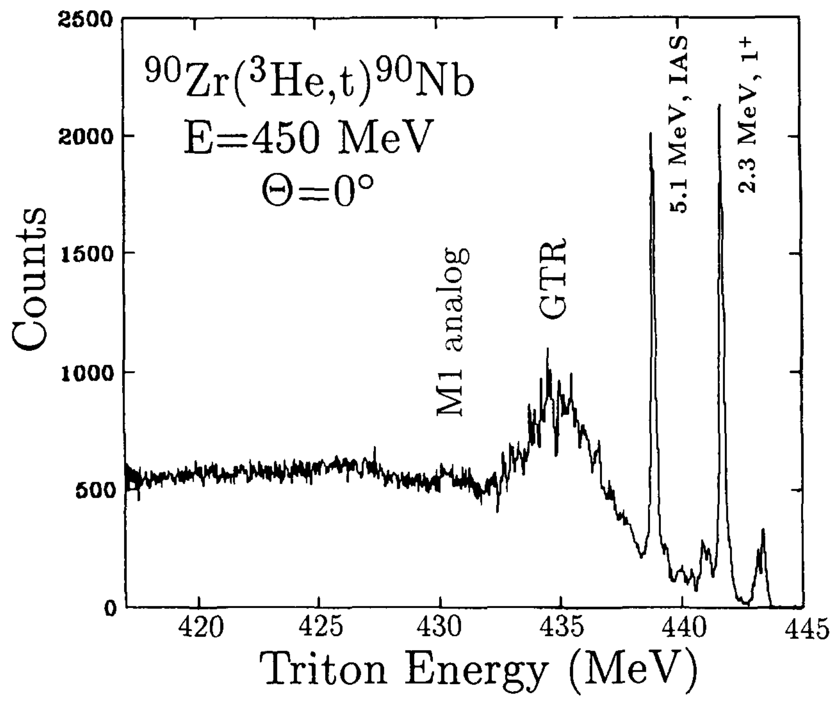

Figure 1 Singles 0° ^{90}Zr(^{3}He t) spectrum taken at E=450 MeV with the spectrometer Grand Raiden The isobaric analog state (IAS) at 5 1 MeV and the 2 3 MeV 1^{+} state are strongly excited A fine structure of the giant Gamow-Teller resonance at 8 9 MeV has been clearly demonstrated

Figure 1 shows an example of the high resolution (^{3}He,t) spectra taken at E=450 MeV In a similar way to the (p,n) measurement at E_p=120 MeV at IUCF [3] our measurement at 150 MeV/u shows a clear enhancement of excitations of the GT states. This similarity is reasonable since the ratio of spin-flip to non-spin-flip contribution $(J_{\sigma\tau}/J_{\tau})^2$ in the (^{3}He,t) reaction is believed to be close to that in the (p,n) reaction at the same bombarding energy per nucleon [15]. Evidently a fine structure of the GT resonance in ^{90}Nb is observed. Fine structures of the GT resonances are also observed in the (^{3}He,t) spectra for other heavy target nuclei like Sb isotopes. An open question to be addressed is the investigation of why this kind of fine structure still exists for the GT resonance in the high excitation energy region above the particle decay threshold where there is an extremely high 1^+ level density.

3. DISCUSSION

3.1. Volume Integrals of the effective interaction

Taddeucci et al. [19] and Bergqvist et al. [15] have shown that the ratio of the 0° cross sections in the charge exchange reaction for transitions to the ground state of ^{12}N and to the 3.51 MeV $3/2^-$ state in ^{13}N is a good measure to check the simplicity of the reaction mechanism. The cross section ratio $\frac{\sigma(^{12}C\rightarrow^{12}N(g.s.))}{\sigma(^{13}C\rightarrow^{13}N(3.51))}$ obtained from the present experiment at 450 MeV was actually about 0.72 at 450 MeV [16], in agreement with the values from the (^{3}He,t) reactions at higher energies. This fact indicates that the single-step process is predominant for the (^{3}He,t) reaction at 450 MeV. It is therefore reasonable to assume that the 0° cross sections are proportional to the GT β-decay strengths B(GT) and to the Fermi transition strengths, B(F).

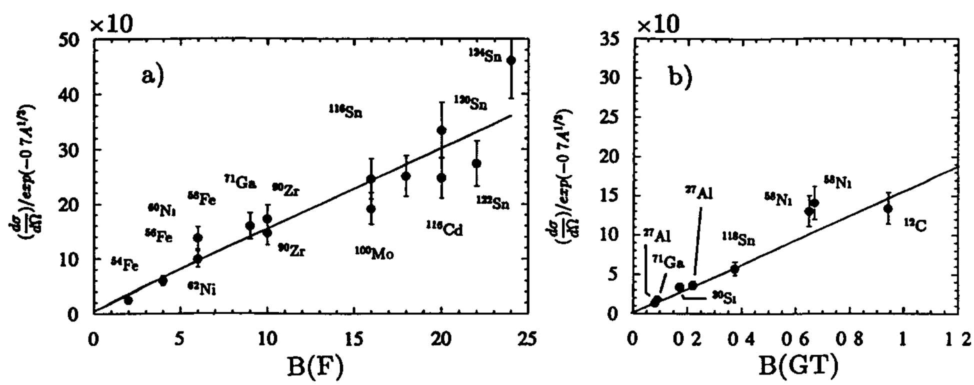

Figure 2. Proportionality of measured 0° (^{3}He,t) cross sections to Fermi and Gamow-Teller transition strengths. The distortion effects are considered in terms of the distortion factor N=exp(-0.7$A^{\frac{1}{3}}$).

The cross sections of the Gamow-Teller state and the IAS can thus be written as [3]

$$\left(\frac{d\sigma}{d\Omega_F}\right)(q\approx 0) = \left(\frac{\mu}{\pi\hbar^2}\right)^2\left(\frac{k_f}{k_i}\right)N_\tau\left(J_\tau\right)^2 B(F), \quad (1)$$

$$\left(\frac{d\sigma}{d\Omega_{GT}}\right)(q\approx 0) = \left(\frac{\mu}{\pi\hbar^2}\right)^2\left(\frac{k_f}{k_i}\right)N_{\sigma\tau}\left(J_{\sigma\tau}\right)^2 B(GT) \quad (2)$$

where the volume integrals of the central part of the effective interaction are J_τ and $J_{\sigma\tau}$, respectively The distortion factors are factorized by N_τ, and $N_{\sigma\tau}$ which may be approximated by the function $\exp(-xA^{\frac{1}{3}})$ [19] The value x is given by $x=2\mu W_I r_0/\hbar^2 k$ where W_I is the depth of the imaginary part of the optical potential The distortion factors are estimated from the cross section ratios calculated in the distorted and plane wave approximations

$$N = \frac{\sigma^{DW}(\theta = 0°)}{\sigma^{PW}(\theta = 0°)} \quad (3)$$

Since there is presently neither reliable optical potential parameters for ^{3}He scattering nor reliable effective interactions at 450 MeV, we apply an empirical method to extract the volume integrals of the effective interaction The cross sections of the IAS for various target nuclei were divided by the distortion factor $N=\exp(-xA^{\frac{1}{3}})$, where the fitting parameter x was determined so as to get a linear relationship between B(F) and the cross sections divided by $N=\exp(-xA^{\frac{1}{3}})$ Here B(F) is well known to be exactly N-Z from the Fermi sum rule The results are shown in Figure 2 With x=0 7, the zero degree differential cross sections are proportional to the Fermi and Gamow-Teller transition strengths respectively The validity of the present experimental relationship for the cross sections of the IAS and GT states should be reconfirmed in future work

With average values of x=0 7 and the well known B(GT) and B(F) values from various target nuclei, the average values of the volume integrals of the effective interactions thus obtained are J_τ=53±5 MeV-fm^3 and $J_{\sigma\tau}$=172±17 MeV-fm^3 respectively The ratio $(J_{\sigma\tau}/J_\tau)^2$ is therefore 10 3±0 5 The values J_τ=89 MeV-fm^3 and $J_{\sigma\tau}$=168 MeV-fm^3 were obtained from the (p,n) experiment at 120 MeV at IUCF [3] The $J_{\sigma\tau}$ value obtained from the (^{3}He,t) reaction at 150 MeV/u is compatible with that obtained from the (p,n) reaction The J_τ value is slightly smaller than that obtained from the (p,n) work at 120 MeV Taking into account that the spin-dependent $\sigma\tau$ central force has a weak energy dependence and the spin-independent central force decreases with increasing bombarding energies toward 150 MeV/u, the present values for the volume integrals of the effective interactions are quite consistent This means that the (^{3}He,t) reaction at 450 MeV is a powerful and reliable probe for extracting GT strengths with the following three advantages, *i e* high resolution low background and high detection efficiency

3.2 Gamow-Teller strength for neutrino detections

In the solar neutrino measurement in Homesteak Mine by Davis [20], ^{37}Cl is used as a neutrino detector target to investigate the nuclear fusion processes in the Sun Since the measurement of the neutrino flux from the Sun reported a significant reduction from the value expected via the Standard Solar Model [7], many controversies and new experimental measurements followed. This reduction of the neutrino flux is called "Solar Neutrino Problem". Among many theoretical explanations, one of the most interesting ideas is the prediction of the neutrino oscillation by the MSW process [21]. The examination of this idea is a current subject of particle physics. Therefore, several projects proposing to check the neutrino flux from the Sun are in progress. Among them, two projects called GALLEX [22] and SAGE [23] use the ^{71}Ga nucleus as a neutrino detector, and a significant reduction of the neutrino flux is reported.

In all cases using nuclear species as neutrino detectors, it is necessary to estimate the neutrino detection sensitivity through the charge current process $A(\nu,e)$. The Gamow-Teller response functions mediated by the operator $\sigma\tau$ are, in principle, measured by charge-exchange reaction experiments. For a long time the (p,n) experiments at IUCF has played an important role in determining neutrino absorption cross sections, because of a good resolution at intermediate energies and a simple reaction mechanism.

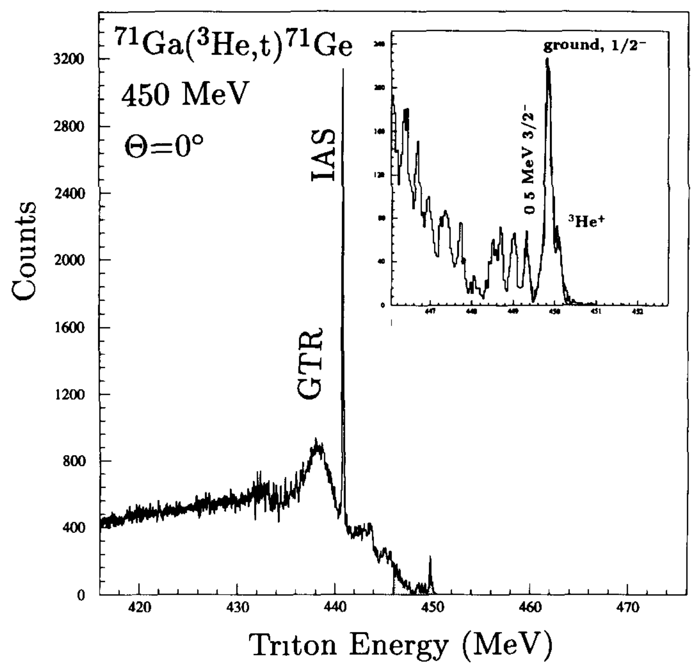

Figure 3. A 0° ^{71}Ga(^{3}He,t) spectrum at 450 MeV. An enlarged display for the region $E_t \geq 446$ MeV is shown. A contamination peak at the right side of the peak for the ground state in ^{71}Ge is due to the background by the atomic charge exchange process of $^{3}He^{2+} \rightarrow {}^{3}He^{+}$.

As mentioned above, the (^{3}He,t) reaction at 450 MeV is a viable complement to the (p,n) reactions because of high resolution and low background Figure 3 shows a ^{71}Ga(^{3}He,t)^{71}Ge spectrum as one such example The relative shape of the present (^{3}He,t) spectrum is quite similar to the (p,n) spectrum taken at 120 MeV [24] The excitation strength of the $3/2^-$ state at 0 175 MeV in ^{71}Ge is found to be very small, which is consistent with the (p,n) result by Krofcheck et al [24], but is not consistent with the low-energy (p,n) result [25] The relative strengths for the 0 0- and 0 175- MeV states are estimated by fitting the peaks at $E_x \leq 0$ 7 MeV with Gaussian shapes The strength of the 0 175 MeV $3/2^-$ state is a factor of about 10 smaller than that for the ground state

By using the known B(GT) value for the ground state in ^{71}Ge, we could extract the preliminary B(GT) values for the excited states The B(GT) results are summarized in Table 1 and will be used to estimate the solar-neutrino capture cross-section in the ^{71}Ga experiment The summed B(GT) value observed below the 7 4 MeV particle decay threshold is 3 1, which is smaller than the (p,n) result by Krofcheck et al [24]

Table 1
GT strengths obtained by the ^{71}Ga(^{3}He,t)^{71}Ge reaction The B(GT) value measured from the β decay experiment for the ground state [26] was used as a calibration point for the present experiment

E_x (MeV)	B(GT)
0 0	0 091
0 17	0 0088
0 5	0 019
0 83	0 025
1 16	0 024
1 36	0 020
1 4~7 42	2 9
total sum ($E_x \leq 7$ 42 MeV)	~ 3 1

4. CONCLUSIONS

The (^{3}He,t) reaction has been measured at 450 MeV at 0° on several target nuclei We achieved a resolution of 130 keV for this (^{3}He,t) reaction The high-resolution (^{3}He,t) measurements at 450 MeV can be a very useful tool in mapping the detailed GT transition strengths in nuclei Strong evidence for the existence of fine structure in the GTR of ^{90}Nb has been shown The volume integrals of the spin-isospin and isospin central forces associated with the (^{3}He t) reactions at 450 MeV are empirically deduced to be $J_{\sigma\tau}$=172±17 MeV-fm^3 and J_τ=53±5 MeV-fm^3 respectively The Gamow-Teller strength function in ^{71}Ge has been measured, which will enable a better estimation of the absorption cross section of solar neutrinos by ^{71}Ga

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